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Λ and $\bar{\Lambda}$ polarization in Au–Au collisions at RHIC

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ABSTRACT

Experiments at RHIC have shown that in 200 GeV Au–Au collisions, the Λ and $\bar{\Lambda}$ hyperons are produced with very small polarizations (Abelev et al., 2007) [1], almost consistent with zero. These results can be understood in terms of a model that we proposed (Barros and Hama, 2008) [2]. In this Letter, we show how this model may be applied in such collisions, and also will discuss the relation of our results with other models, in order to explain the experimental data.

Since the discovery of significant polarization for the Λ particles produced in 100 GeV p–Be collisions by Bunce [3], hyperon polarization has shown to be a very challenging subject, as, at the time it was a totally surprising result. This fact, unexpected both experimentally and theoretically has been confirmed by further experiments, and this puzzle has been complicated when the polarizations of the other hyperons and antihyperons have been measured [4–11].

Hyperon polarization may be quite well described by parton-based models [12–14], but antihyperon polarization not. In [2], we proposed a model that was able to describe successfully the antihyperon polarization in terms of final-state interactions that occur in the hadronic phase of such collisions, in a mechanism based in relativistic hydrodynamics.

Recently, at RHIC, in 200 GeV Au–Au collisions, the Λ and $\bar{\Lambda}$ polarizations have been measured [1], as functions of the transverse momentum, in the range $0 < p_t < 5$ GeV, and as functions of the pseudorapidity, in the range $-1.5 < \eta < 1.5$. In this region, the final polarization for both particles may be considered consistent with zero. The polarizations have been measured in the direction orthogonal to the reaction plane, that is a plane determined by the direction of the impact parameter $\vec{b}$, and the beam direction. As it was suggested in [15], zero polarization in high energy nucleus–nucleus interactions, if observed, could show a signal of quark–gluon plasma formation. Some models show good results in explaining Λ and $\bar{\Lambda}$ polarizations. In [18–20], this effect is proposed as the partons are produced with large angular momentum, and quark polarization results from parton scattering. In [16,17] polarization of spin 1/2 particles for an equilibrated system is computed.

As we can see, this is a very important problem, and the objective of this Letter is to study this question, showing some results that we obtained, and discussing their relations with other theoretical results. We will apply the model that we used to calculate antihyperon polarization in p–A collisions, in the study of the Au–Au collisions performed at RHIC. In [2], we have shown that significant polarization may occur considering this model. We investigate the effect of the final-state interactions in nucleus–nucleus collisions and if it is possible that these interactions may affect the final polarization of the produced particles. This model is based on the hydrodynamical aspects of such collisions, so, the first step is to obtain the velocity distribution of the fluid formed during the collision. Then, we will use it in order to obtain the average polarization, taking into account the $\pi\Lambda$ and $\pi\bar{\Lambda}$ final interactions.

In the hydrodynamical picture, in the collision of two high-energy particles, the large amount of energy localized in a very small volume produces a fluid, that expands and then produces the final particles, what may be understood by the freeze-out mechanism. We will suppose a parametrization of the velocity distribution of such fluid given by the expression

$$u^0 \frac{d\rho}{d^3u} = A\left[e^{-\beta(\alpha-\alpha_0)^2} + e^{-\beta(\alpha+\alpha_0)^2}\right]e^{-\beta_t\xi^2}, \tag{1}$$

that is written in terms of its longitudinal (α) and transversal (ξ) rapidities. That means that the formed fluid expands in the

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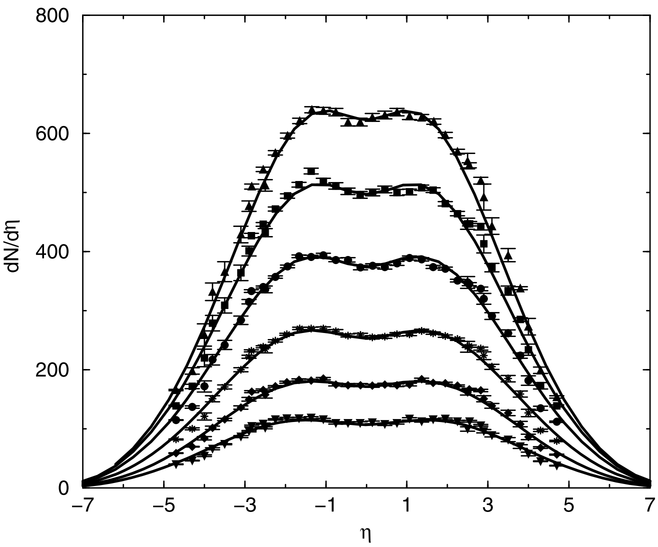

Fig. 1. Distributions $dN/d\eta$, for many centralities. From the top, 0–5%, 5–10%, 10–20%, 20–30%, 30–40%, 40–50%. We compare our results (solid lines), with the experimental data from [24] (points).

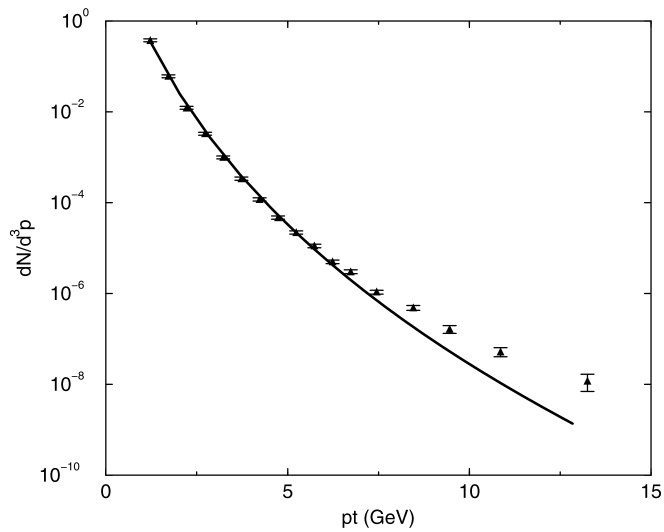

Fig. 2. Comparison of the calculated distribution dN/d^3p as function of p_t with the experimental data from [23].

incident nuclei direction (α), and also in the transverse direction (ξ). This kind of velocity distribution has shown to describe correctly the production of particles in many other systems [21,22]. We may visualize this fluid geometrically, in a first approximation, as an hot expanding cylinder. The constants β, β_t and α_0 are parameters that describe the shape of this distribution. They are determined by calculating the distributions of the produced particles, and, comparing them with the RHIC experimental data for the transverse momentum p_t [23] and pseudorapidity (η) distributions [24].

This objective may be achieved, making a convolution of the fluid velocity distribution (1), with the particles distribution, inside these fluid elements, that may be considered a Bose distribution as most of the produced particles are pions. We will consider

$$\frac{dN}{d\vec{p}_0} = \frac{N_0}{\exp(E_0/T) - 1} \tag{2}$$

with the temperature $T \sim m_\pi$, and $\vec{p}_0$ and E_0 are the momentum and energy of the pions inside one fluid element. So, the observed distributions of particles are given by

$$E\frac{dN}{d\vec{p}} = C\int \left[e^{-\beta(\alpha-\alpha_0)^2} + e^{-\beta(\alpha+\alpha_0)^2}\right]e^{-\beta_t\xi^2} \times \frac{E_0(\alpha,\xi,\phi)}{\exp\left(E_0(\alpha,\xi,\phi)/T\right) - 1}\sinh\xi\cosh\xi\, d\alpha\, d\xi\, d\phi, \tag{3}$$

where ϕ is the azimuthal angle. The results of the particles distributions resulting from Eq. (3) are shown in Figs. 1 and 2. We obtained a very good description of $d\sigma/d\eta$ for all centralities (Fig. 1), and for the p_t distribution (Fig. 2), the results are very good for $p_t < 6$ GeV. For $p_t > 6$ GeV, a small discrepancy may be noticed, and it increases with p_t. This fact is not a problem for the present work, as in the experimental data for polarization, the values of p_t investigated are below this value. This problem shows that other processes become important at large p_t, such as the hard scattering ones. A way to improve the results is to insert an extra term, depending on the transverse rapidity of the fluid ξ, in Eq. (1), what represents alterations in the equation of state. For simplicity, it will not be done in this Letter.

The parameters obtained are $\beta = 0.14$, $\beta_t = 3.2$ and α_0 in the range 1.5–1.75, varying with the centrality, as it can be seen in Table 1. We can observe that β and β_t does not seem to have any dependence on the centrality.

Table 1
Values of the parameters β, β_t and α_0 of the curves shown Figs. 1 and 2.

Centrality	β	β_t	α_0
0–5%	0.14	3.2	1.50
5–10%	0.14	3.2	1.56
10–20%	0.14	3.2	1.62
20–30%	0.14	3.2	1.67
30–40%	0.14	3.2	1.70
40–50%	0.14	3.2	1.75

Observing these results, one may see that the fluid parametrization, with the velocities distributions given by (1), is very reasonable and describes quite well the experimental data in the region of our interest. So, considering this description, we may calculate the polarization of a hyperon (or antihyperon) produced in the interior of such system, taking into account the effect of the final-state interactions, of these particles with the surrounding pions (that is the dominant effect), as we made in [2].

Now, let us turn our attention to the final-state interactions. The most important case to be considered is the $\pi\Lambda$ ($\pi\bar{\Lambda}$), as it is the most probable interaction. The relative energy of this interaction is not so high, despite the fact that these particles are observed with high energies in the laboratory system of reference. This interaction may be described by effective chiral Lagrangians, as we made in [26–28], where the resonance $\Sigma^*(1385)$ in the intermediate state is a key element. These Lagrangians are

$$\mathcal{L}_{\Lambda\pi\Sigma} = \frac{g_{\Lambda\pi\Sigma}}{2m_\Lambda}\{\bar{\Sigma}\gamma_\mu\gamma_5\vec{\tau}\Lambda\}.\partial^\mu\vec{\phi} + \text{h.c.},$$
$$\mathcal{L}_{\Lambda\pi\Sigma^*} = g_{\Lambda\pi\Sigma^*}\left\{\bar{\Sigma}^{*\mu}\left[g_{\mu\nu} - \left(Z+\frac{1}{2}\right)\gamma_\mu\gamma_\nu\right]\vec{\tau}\Lambda\right\}.\partial^\nu\vec{\phi} + \text{h.c.}, \tag{4}$$

where $\vec{\phi}$ is the pion field and Z is a parameter representing the possibility of the off-shell-resonance having spin 1/2.

The considered diagrams for the scattering amplitude are shown in Fig. 3. The scattering amplitude determines the cross sections $d\sigma/d\Omega$ and $d\sigma/dt$, and the polarization. More details on the calculations may be found in [2,27] and [26]. The Λ

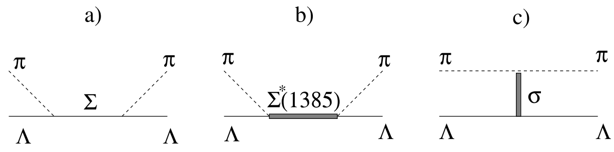

Fig. 3. Diagrams for $\pi\Lambda$ interaction.

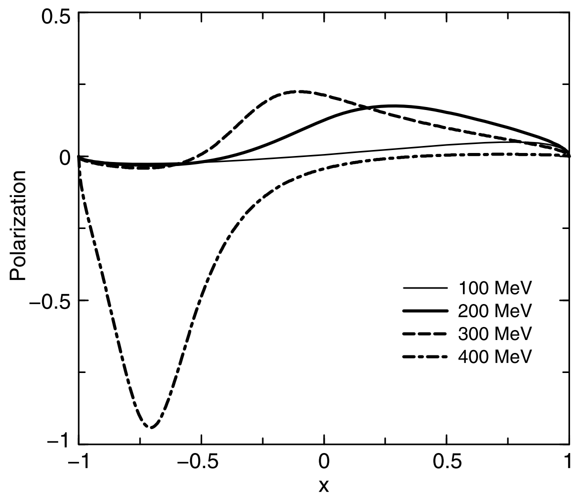

Fig. 4. Polarization in the $\pi\Lambda$ interaction as function of $x = \cos\theta$, for some values of the pion momentum, in the $\pi\Lambda$ center-of-mass system [26].

polarization, as a function of $x = \cos\theta$, where θ is the scattering angle, is shown in Fig. 4.

One must observe that this model, that we proposed in 2001 [26], has made a very good prediction for the $\pi\Lambda$ phase shift at the Ξ mass, $\delta_P - \delta_S = 4.3°$, result that has been confirmed experimentally at the Fermilab in the HyperCP experiment in 2003 [29, 30], where they obtained $\delta_P - \delta_S = (4.6 \pm 1.4 \pm 1.2)°$. This result validates our model for the $\pi\Lambda$ interaction.

With the knowledge of the velocities distribution, shown in Figs. 1 and 2, and of the final interactions (Fig. 4), we are able to calculate the average polarization of the produced particles in the same way we made in [2].

The average polarization may be calculated by the expression

$$\langle\vec{P}\rangle = \frac{\int(\vec{P}' d\sigma/dt)\mathcal{G}\,d\alpha\,d\xi\,d\phi\,d\vec{\Lambda}'_0\,d\vec{\pi}'_0}{\int(d\sigma/dt)\mathcal{G}\,d\alpha\,d\xi\,d\phi\,d\vec{\Lambda}'_0\,d\vec{\pi}'_0}, \tag{5}$$

where $\vec{\Lambda}'_0$ is the Λ momentum and $\vec{\pi}'_0$ is the pion one. The factor $\mathcal{G}$ that appears in Eq. (5) contains the statistical weights of the production of the particles and the ones relative to the expansion of the fluid, and can be written as

$$\mathcal{G} = \frac{(d\rho/d^3u)}{(\exp(E'_{\pi_0}/T) - 1)(\exp(E'_0/T) + 1)} \Lambda_0'^2 \pi_0'^2 \times \delta\Big(E'_0 + E'_{\pi_0} - E' - \sqrt{m_\pi^2 + (\vec{\pi}'_0 + \vec{\Lambda}'_0 - \vec{\Lambda}')^2}\Big), \tag{6}$$

where $d\rho/d^3u$, is given by (1).

With this procedure we obtained the results shown in Figs. 5 and 6. As we can see, the resulting polarization is very small (smaller than 1%) for all values of the centrality, and are in good accord with the experimental data for both Λ and $\bar{\Lambda}$.

It is known that in high energy p–A collisions [3], the $p \to \Lambda$ process, produces polarized Λ hyperons. This result may be explained in terms of a quark exchange, of the type $u \to s$, where an u quark of the incoming proton is exchanged by a s quark, and

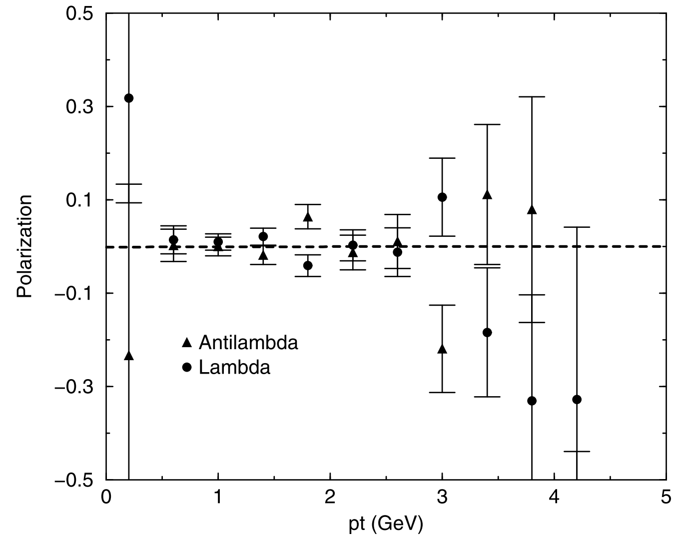

Fig. 5. Calculated polarization (dashed line) as function of p_t compared with the experimental data from [1].

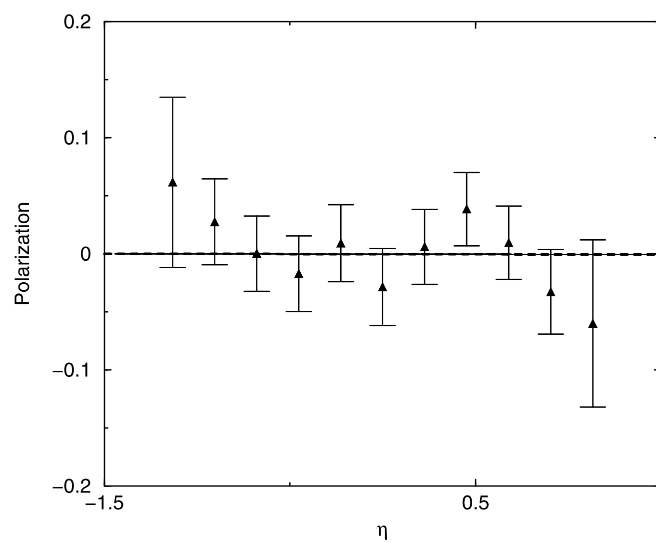

Fig. 6. Calculated polarization (dashed line) as function of η compared with the experimental data from [1].

this reaction leads to significant polarization, transversal to the reaction plane. In A–A collisions this effect is not expected to occur. As pointed by Panagiotou in 1986 [15], a vanishing polarization should be considered as a sign of quark–gluon plasma formation. In [18–20] the polarization of such reactions is well studied, and it has been shown that a very small polarization is expected. As it was shown in [25], if we consider a polarized parton, produced in the interior of a quark–gluon plasma, that is estimated to have a lifetime of the order of $t_{QGP} \sim 10$ fm/c (at RHIC in 200 GeV collisions, about 6 fm/c) [33,34], and observing that the mean free path of the partons inside the plasma is relatively large, the effect of successive scattering is to attenuate this polarization. Interesting ideas about these processes may be found in [16,17]. In [25], vortices formation inside the plasma is studied, and this mean free path is related to the size of the radius of curvature within the formed vortex. So, according to the models above, in high energy collisions, the hyperons are produced unpolarized, or, with an almost negligible polarization. Considering now the rescattering in the hadronic phase, that has a lifetime about 2–3 t_{QGP}, it is expected that this polarization becomes smaller, and even the information of the initial plane of production may be lost. But what should happen if the final-state interactions are considered?

Final-state interactions is a kind of effect that is very important in many systems, as for example, in the study of *CP* violation in non-leptonic hyperon decays, where the final amplitude is determined by the amplitude resulting from the final-state strong interactions [28,31,32]. As we have shown [2], this effect is fundamental in the understanding of the polarization of antihyperons in p–A collisions, where unpolarized hyperons may become polarized. So, it is very reasonable to think that something similar might occur in heavy-ion collisions, where the systems are very large, and the energy, very high. In a system, such as a RHIC collision, the probability of final interactions increase, and this effect becomes more important. The question is if a unpolarized produced Λ, may become polarized, after the final interactions.

As we verified, in p–A collisions [2], significant polarization in the direction normal to the plane determined by the hyperon and beam directions (production plane), may be obtained when unpolarized particles interact near the surface, as for example in the $\bar{\Xi}^+$ production. So, a question that may be proposed, is if this effect could have some relation with the recent data obtained in the direction normal to the reaction plane, and some residual polarization could be observed. In this Letter, performing the calculations, we have shown that the final polarization remains very small (almost negligible), and this fact is due to two reasons: The first, and probably the most important one, is that the asymmetry in the polarization occurs due to the asymmetry of the system, what is determined by the parameter β, that shows the shape of the rapidity distribution. For large values of β ($\sim$2–3, that appears in p–A collisions), in the forward direction this distribution is sharp, and polarization occurs. In Au–Au collisions, as we have shown, β is very small ($\beta = 0.14$ for the data studied in this Letter), so the distribution is smooth, what determines cancellation of the final polarization. The second reason, is that the Λ polarization in the $\pi\Lambda$ interaction is not large for most of the incident energies. If we observe Fig. 4, we may notice that it is positive and smaller than 0.25 for most of the energies, and becomes negative for higher energies. But for these energies, the statistical weight is much smaller. When the average has been calculated, it was almost totally washed out. In fact, this effect also occurred in [2], where the final Λ and $\bar{\Lambda}$ polarizations were very small. On the other hand, in [2], considering other hyperons and antihyperons, large final polarization (consistent with the experimental data) has been obtained.

So, the mechanism that is responsible for the polarization in p–A collisions, in high energy A–A collisions has exactly the opposite effect, and destroys most of the signs of polarization. We must remark the consistency of the hydrodynamical approach for these collisions that works for p–A and for A–A collisions.

Observing these facts we can conclude that when the polarization is small in pp and pA collisions, measured the production plane, it will be small in AA collisions, in the reaction plane, as it was shown in this Letter for Λ and $\bar{\Lambda}$ (in fact, the polarization will be much smaller in AA collisions). For the other hyperons, (Σ, Ξ and the antihyperons, see [2]), that are produced with significant polarizations in pA collisions (up to 30% in some cases), we also expect that in AA collisions, such as the RHIC systems, the polarization measured in the reaction plane becomes smaller. An interesting question is if this polarization is totally washed out or some polarization may be observed. This question shall be discussed in a next work.

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